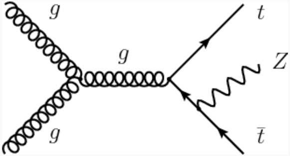
$t\bar{t}Z$ measurements: results, path forward.

• Marek Niedziela

EOS be.h Winter Solstice Meeting

16th of December, 2020

Top pair production in association with Z boson



⇒ Theory x-section: 0.86 pb ± 8%

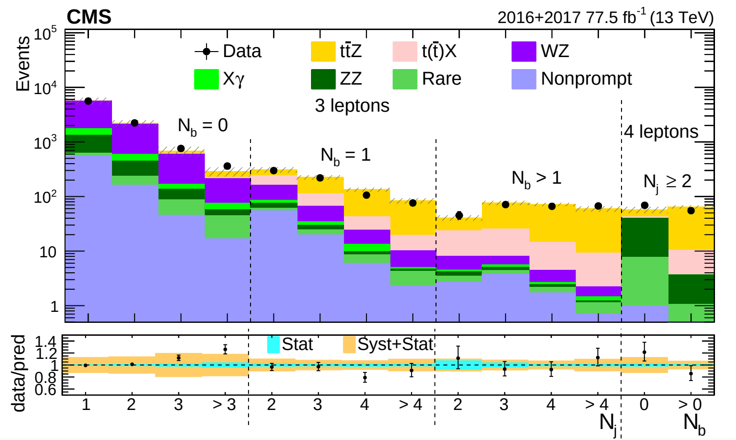
⇒ 2016+2017 measurement: 0.95 pb ± 8%

⇒ Run2 ATLAS measurement: 1.05 pb ± 10%

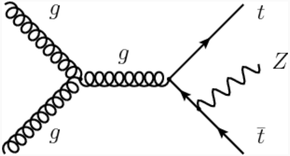
- Direct probe of the coupling of top quark and Z boson.
- Test of Standard Model prediction.
- Important background for other ttV processes, e.g. ttH.
- But also: sensitive to potential new physics.

Background estimation, search regions

- **Nonprompt ℓ (data-driven)**
  - → estimated directly from data by measuring and applying "tight-to-loose" ratio.
- **Diboson processes WZ and ZZ (MC)**
  - → WZ is the main source of systematic uncertainty.
- **t($\bar{t}$)X (MC)**
  - → main contribution comes from tZq and tWZ processes, includes also ttH.
- **Photon conversions Xγ (MC)**
- **Rare (MC)**



CMS 77.5 fb^{-1} results (2016+2017)



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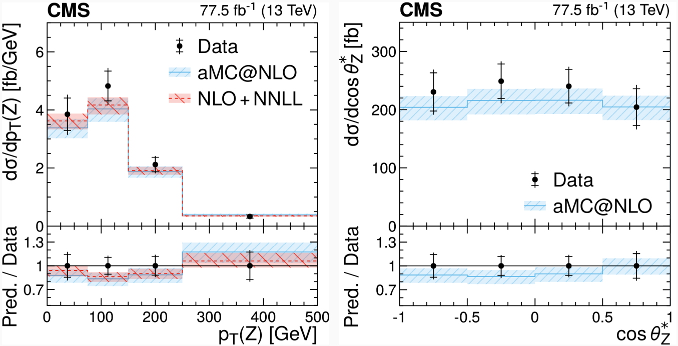
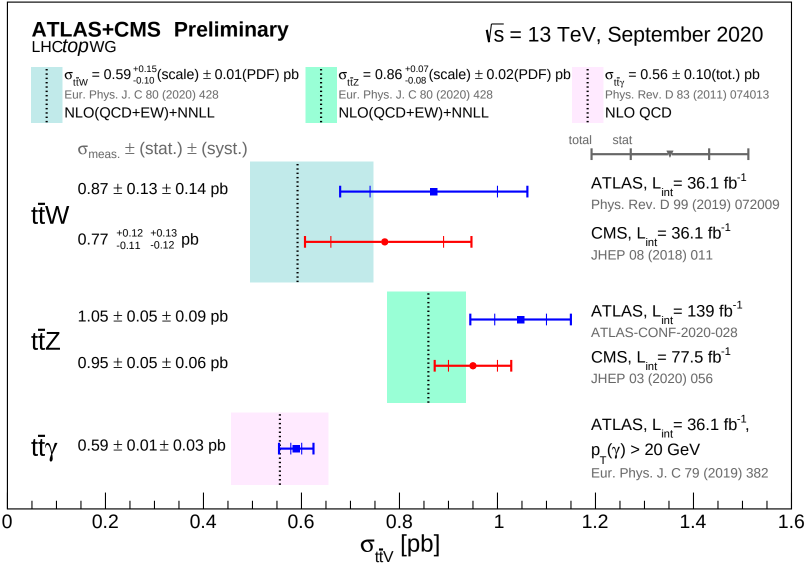


Great cooperation with theorists **1812.08622**, **1905.07815**

Inclusive results summary



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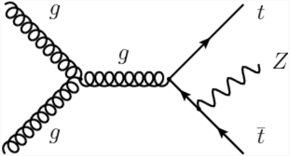

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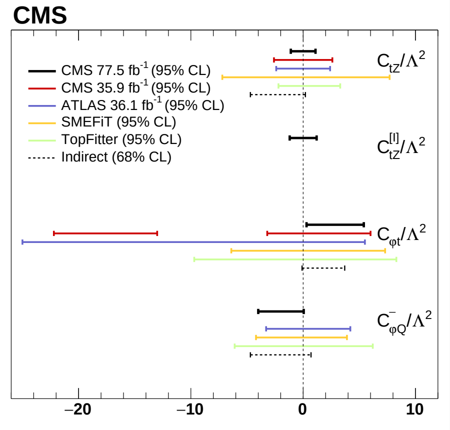
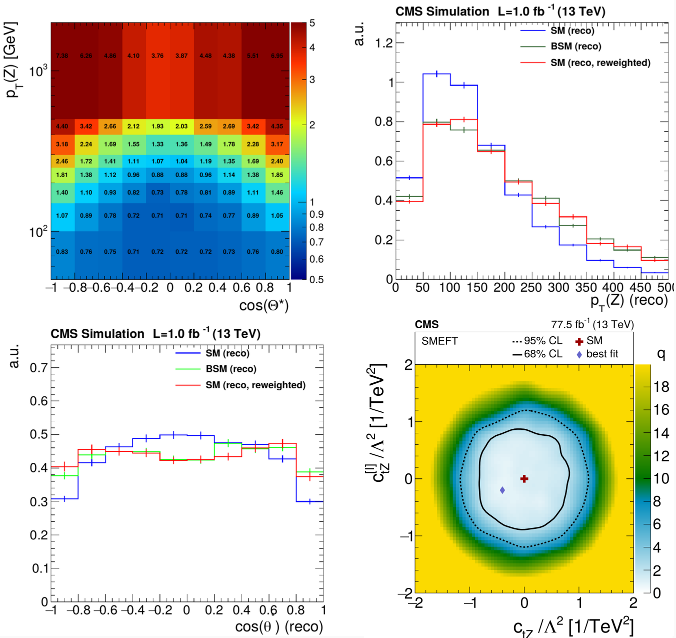
$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

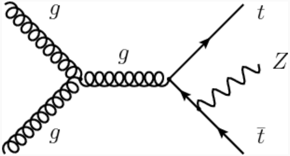
- d dimension
- Λ mass scale
- c Wilson coefficients
- $\mathcal{O}^{(d)}$ effective operators of dimension d



CMS 77.5 fb^{-1} (2016+2017) EFT approach



CMS full run 2 results?



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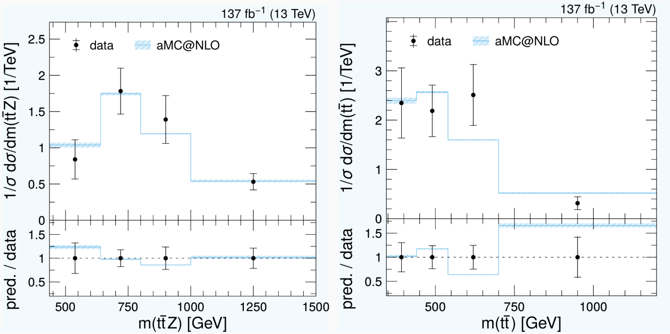
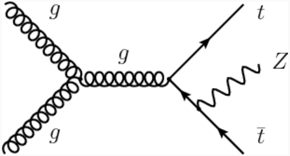
⇒ Current CMS Run2 result: ??? pb ± **7%**



Distributions from thesis **J. Knolle**, theory from **[1]**, **[2]**, **[3]**

CMS full run 2 results: What about EFT



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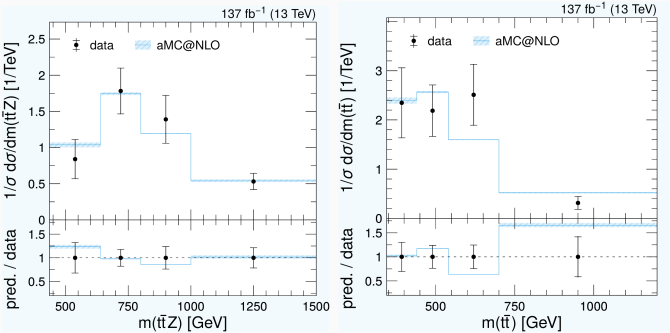

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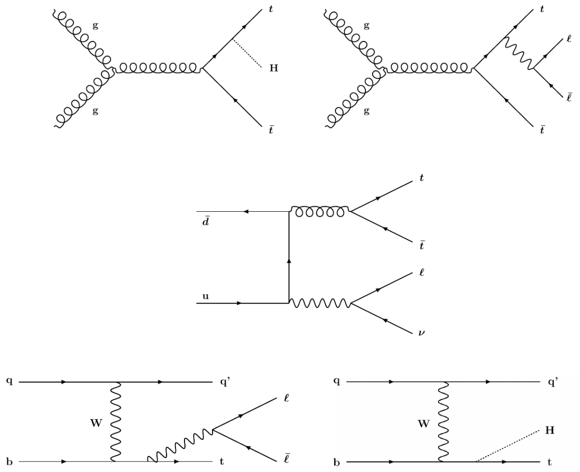
CMS ttV EFT analysis

CMS recently published **ttV EFT analysis**, targeting multiple signals with one or more top quarks produced in association with additional leptons.



CMS ttV EFT analysis

- It's not possible to isolate samples pure in each contribution, so each search region is populated by events from different processes, e.g. ttZ and tZq.
- Each EFT operator can contribute to multiple processes, which requires simultaneous analysis of all considered operators across all search regions.

Operators involving two quarks and one or more bosons			
Operator	Definition	WC	Processes affected
‡$O_{u\varphi}^{(ij)}$	$\overline{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi)$	$c_{t\varphi} + ic^I_{t\varphi}$	$t\bar{t}H$, tHq
$O_{\varphi q}^{1(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\overline{q}_i\gamma^\mu q_j)$	$c^-_{\varphi Q} + c^3_{\varphi Q}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$O_{\varphi q}^{3(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\overline{q}_i\gamma^\mu\tau^I q_j)$	$c^3_{\varphi Q}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$O_{\varphi u}^{(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\overline{u}_i\gamma^\mu u_j)$	$c_{\varphi t}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$
‡$O_{\varphi ud}^{(ij)}$	$(\tilde{\varphi}^\dagger iD_\mu\varphi)(\overline{u}_i\gamma^\mu d_j)$	$c_{\varphi tb} + ic^I_{\varphi tb}$	$t\bar{t}H$, $tl\bar{l}q$, tHq
‡$O_{uW}^{(ij)}$	$(\overline{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi}W^I_{\mu\nu}$	$c_{tW} + ic^I_{tW}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
‡$O_{dW}^{(ij)}$	$(\overline{q}_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi W^I_{\mu\nu}$	$c_{bW} + ic^I_{bW}$	$t\bar{t}H$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
‡$O_{uB}^{(ij)}$	$(\overline{q}_i\sigma^{\mu\nu}u_j)\,\tilde{\varphi}B_{\mu\nu}$	$(c_W c_{tW} - c_{tZ})/s_W +$ $i(c_W c^I_{tW} - c^I_{tZ})/s_W$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
‡$O_{uG}^{(ij)}$	$(\overline{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{\varphi}G^A_{\mu\nu}$	$c_{tG} + ic^I_{tG}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$

Operators involving two quarks and two leptons			
Operator	Definition	WC	Processes affected
$O_{\ell q}^{1(ijkl)}$	$(\overline{\ell}_i\gamma^\mu\ell_j)(\overline{q}_k\gamma^\mu q_\ell)$	$c^{-(\ell)}_{Q\ell} + c^{3(\ell)}_{Q\ell}$	$t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$
$O_{\ell q}^{3(ijkl)}$	$(\overline{\ell}_i\gamma^\mu\tau^I\ell_j)(\overline{q}_k\gamma^\mu\tau^I q_\ell)$	$c^{3(\ell)}_{Q\ell}$	$t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$
$O_{\ell u}^{(ijkl)}$	$(\overline{\ell}_i\gamma^\mu\ell_j)(\overline{u}_k\gamma^\mu u_\ell)$	$c^{(\ell)}_{t\ell}$	$t\bar{t}l\bar{l}$
$O_{eq}^{(ijkl)}$	$(\bar{e}_i\gamma^\mu e_j)(\overline{q}_k\gamma^\mu q_\ell)$	$c^{(\ell)}_{Qe}$	$t\bar{t}l\bar{l}$, $tl\bar{l}q$
$O_{eu}^{(ijkl)}$	$(\bar{e}_i\gamma^\mu e_j)(\overline{u}_k\gamma^\mu u_\ell)$	$c^{(\ell)}_{te}$	$t\bar{t}l\bar{l}$
‡$O_{\ell equ}^{1(ijkl)}$	$(\overline{\ell}_i e_j)\,\varepsilon\,(\overline{q}_k u_\ell)$	$c^{S(\ell)}_t + ic^{SI(\ell)}_t$	$t\bar{t}l\bar{l}$, $tl\bar{l}q$
‡$O_{\ell equ}^{3(ijkl)}$	$(\overline{\ell}_i\sigma^{\mu\nu}e_j)\,\varepsilon\,(\overline{q}_k\sigma_{\mu\nu}u_\ell)$	$c^{T(\ell)}_t + ic^{TI(\ell)}_t$	$t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$

How to parametrize impact of BSM on event?

To be able to measure the effects of new physics on the observed yields, one has to parametrize the yields in Wilson Coefficients. The matrix element can be written as a sum of SM and new physics components (restrained to $\mathcal{O}(6)$ operators):

$$\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{M}_i. \tag{1}$$

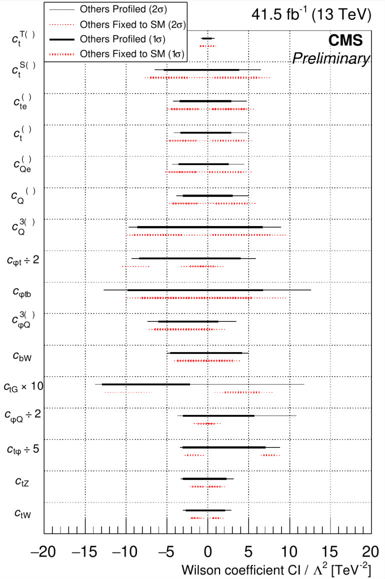
Cross section is proportional to the square of matrix element. The event weight can be expressed as

$$w(\frac{\vec{c}}{\Lambda^2}) = s_0 + \sum_i s_{1i}\frac{c_i}{\Lambda^2} + \sum_i s_{2i}\frac{c_i^2}{\Lambda^4} + \sum_{i,j} s_{3ij}\frac{c_i}{\Lambda^2}\frac{c_j}{\Lambda^2} \tag{2}$$

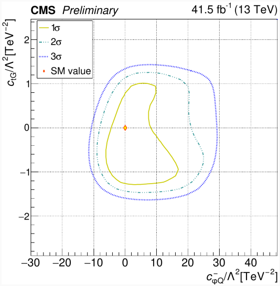
The yield in given event category becomes also a function of the s_N and c_i coefficients and can be expressed as:

$$N(\frac{\vec{c}}{\Lambda^2}) = S_0 + \sum_i S_{1i}\frac{c_i}{\Lambda^2} + \sum_i S_{2i}\frac{c_i^2}{\Lambda^4} + \sum_{i,j} S_{3ij}\frac{c_i}{\Lambda^2}\frac{c_j}{\Lambda^2} \tag{3}$$

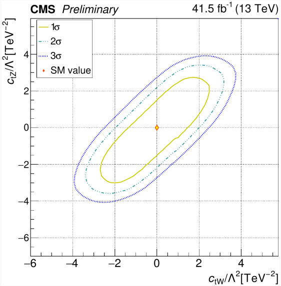
Results



Others Profiled (2σ)
Others Fixed to SM (2σ)
Others Profiled (1σ)
Others Fixed to SM (1σ)
41.5 fb-1 (13 TeV)
CMS
Preliminary
c_{tZ}
c_{tW}
c_{bW}
c_{tG} × 10
$c_{\varphi Q}$ ÷ 2
$c_{t\varphi}$ ÷ 5
$c_{\varphi t}$ ÷ 2
$c_{\varphi tb}$
–20 –15 –10 –5 0 5 10 15 20
Wilson coefficient CI / Λ^2 [TeV^{-2}]



CMS Preliminary
41.5 fb-1 (13 TeV)
1σ
2σ
3σ
SM value
c_{tG}/Λ^2[TeV^{-2}]
$c^{-}_{\varphi Q}/\Lambda^2$[TeV^{-2}]



CMS Preliminary
41.5 fb-1 (13 TeV)
1σ
2σ
3σ
SM value
c_{tZ}/Λ^2[TeV^{-2}]
c_{tW}/Λ^2[TeV^{-2}]

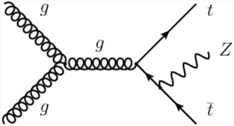
Results

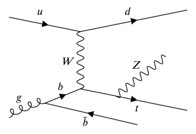
Coefficient	ttZ paper	ttV paper
c_{tZ}	[-1.1,1.1]	[-3.32,2.15]
$c_{\phi t}$	[0.3,5.4]	[-18.62,12.31]

- Results presented in ttZ paper benefit from optimized search regions and larger dataset.
- Furthermore, in ttZ paper only 4 coefficients are considered and a completely different approach is exploited.
- Framework developed for ttV measurement provides a flexible approach, allowing to a simultaneous treatment of several signals with BSM yields taken per event from MC rather than by reweighting.
- The ttV approach offers a broader view while using a simple search regions definitions. It is a new method and both measurement types can be treated as complimentary.
- With an analysis framework for several ttV processes, one could think of applying the new approach parallel to the procedure used for dedicated searches.

On-going efforts at UGent

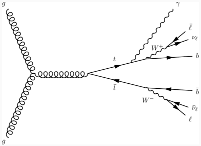
- ⇒ **$t\bar{t}$Z** full run 2 : inclusive measurement, expected to reduce measurement uncertainty from 8% to 7%.
- ⇒ Extended measurement of differential cross section.
- ⇒ Plans for EFT interpretation, possibly combined with tZq.
- ⇒ Project run by me and J. Knolle, fellow **EOS postdoc**.

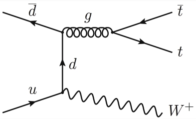




- ⇒ **tZq** full run 2 : inclusive measurement, expected to reduce measurement uncertainty from 15% to 11%.
- ⇒ Plans for EFT interpretation, possibly with ttZ.

- ⇒ **$t\bar{t}$**γ full run 2 : inclusive x-sec, expected uncertainty ≈6.4%.
- ⇒ First measurement of differential cross section.
- ⇒ EFT interpretation for c_{tZ} and c^{I}_{tZ}.
- ⇒ **First** CMS results on that process.





- ⇒ **ttW** full run 2 : inclusive measurement, expected to reduce measurement uncertainty from 23%.
- ⇒ Plans for EFT interpretation.
- ⇒ **EOS PhD** student T. Tran working on this project.

Thank you for your attention!

Back-up

Object selection

Electrons

⇒ $p_T > 10$ GeV, $|\eta| < 2.5$

⇒ Missing inner hits ¡ 2

Muons

⇒ $p_T > 10$ GeV, $|\eta| < 2.4$

⇒ Medium POG ID, PFMuon, tracker or global

All Leptons

⇒ $|d_{xy}| < 0.05$ cm, $|d_z| < 0.1$ cm, $SIP_{3D} < 8$

⇒ miniisolation: $I_{mini} < 0.4$

⇒ **TOP Lepton MVA** Loose ID :

> 0.0 (electrons) and > 0.05 (muons)

Jets

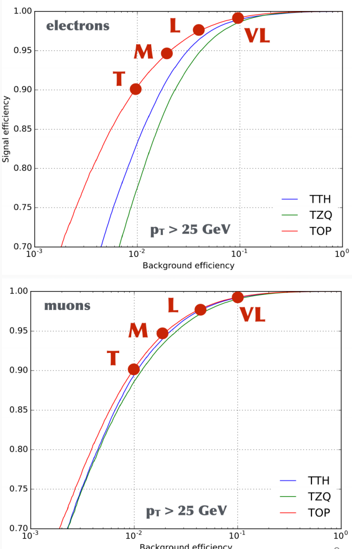
⇒ $p_T > 30$ GeV, $|\eta| < 2.4$

⇒ loose (tight) POG ID

⇒ well separated from any lepton

⇒ b-tagging: DeepFlavor medium WP

Lepton MVA ID



Event selection

3ℓ final state

⇒ 3 leptons with $p_T > 40,20,10$ GeV

⇒ one OSSF lepton pair 10 GeV close to Z

4ℓ final state

⇒ 4 leptons with $p_T > 40,10,10,10$ GeV

⇒ one OSSF lepton pair 20 GeV close to Z

Event categorisation

⇒ **inclusive measurement** → 14 exclusive categories for fit:

N(ℓ)	**N(j)**	**N(b)**
3	1, 2, 3, ≥ 4	0
3	2, 3, 4, ≥ 5	1, ≥ 2
4	≥ 2	0, ≥ 1